

Probabilistic Models for Pedestrian Capacity and Delay at Roundabouts

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ABSTRACT

The increase of the popularity of modern roundabouts in urban settings creates the need to assess their impact on pedestrian delays and capacities. The subject paper presents an analytical approach for calculation of pedestrian crossing capacity and pedestrian delay at roundabouts. Comparisons between pedestrian capacity and delays at roundabouts and signalized intersections are also provided.

The pedestrian crossing capacity is conceptualized with the help of the maximum pedestrian crossing rate (MPCR). The latter is based on a probabilistic gap acceptance model. The model is made possible with the following practical assumptions: (a) priority cannot be given to the pedestrian at the crosswalk of roundabouts and (b) arrival rate of approaching vehicles follows the probabilistic distribution.

The MPCR at signalized intersections is calculated based on the existing pedestrian capacity model of HCM considering signal phases and timing.

As MPCR for both intersection alternatives are proposed, the resulting delays can be also calculated and compared. Queuing theory principles under M/M/1 (∞ , FIFO) conditions are employed for this purpose. These conditions represent random arrivals and departures, one server, and service of vehicles in the order they arrive (first-in-first-out principle). Capacity and delay are compared for a set of experimental conditions. The results indicate that roundabouts provide more capacity than signalized intersections for approaching traffic of up to 1000 veh/h/direction. The comparison of pedestrian delays confirms the intuitive concept that roundabouts can provide lower pedestrian delay under light vehicle and pedestrian traffic.

In this paper, the MPCR model for calculation of pedestrian capacity and delay at roundabouts has been suggested and experimental results from model application are presented and discussed. These models, concepts, and results themselves may be useful to evaluate performance of roundabouts with respect to pedestrians. Employment of alternative

arrival distributions is expected to enhance applicability, accuracy, and diversity of this model and is recommended for future studies.

1. BACKGROUND

The safety and the effectiveness of roundabouts were established after roundabouts employed several operational and design elements. There are three such main elements, namely, yield at entry, deflection of vehicle paths, and entry flare. These elements distinguish the modern roundabout from traditional circles. Additional elements for the qualified roundabout are dividing islands at all approaches, good sight distance, and appropriate signing.

The elements presented above create unique conditions for pedestrian traffic. Pedestrian crossing is possible only when a gap is equal to or in excess of the acceptable gap. These concepts are presented in the Florida Roundabout Guide (1995) and the Roundabout Design Guidelines (1995). The existence of dividing islands could affect pedestrian delay in the sense that pedestrians spend time identifying another acceptable gap while on the dividing island. On the other hand, delay may be decreased since the minimum acceptable gap for a two-staged pedestrian crossing is half the gap required for a full-staged pedestrian crossing. Figure 1 offers a schematic drawing of vehicle and pedestrian movements at a roundabout.

2. OBJECTIVES

This study proposes a model of maximum pedestrian crossing rate (MPCR) at roundabouts and then calculates and compares the crossing delays experienced by pedestrians at roundabouts and signalized intersections. The study objectives are to (a) model pedestrian capacity and delay at roundabouts, and (b) compare the performance of roundabouts and signalized intersections under various conditions in terms of pedestrian capacity and delay. To achieve these objectives the study is organized as follows:

1. MPCR at roundabouts are determined in terms of approaching vehicle flow rates and pedestrian crosswalk length;
2. MPCR at signalized intersections are determined in terms of cycle lengths and pedestrian crosswalk lengths;
3. Pedestrian delay at roundabouts is modeled;
4. Pedestrian delay at signalized intersections is modeled; and
5. MPCR and delays are computed for signalized intersections and roundabouts and compared.

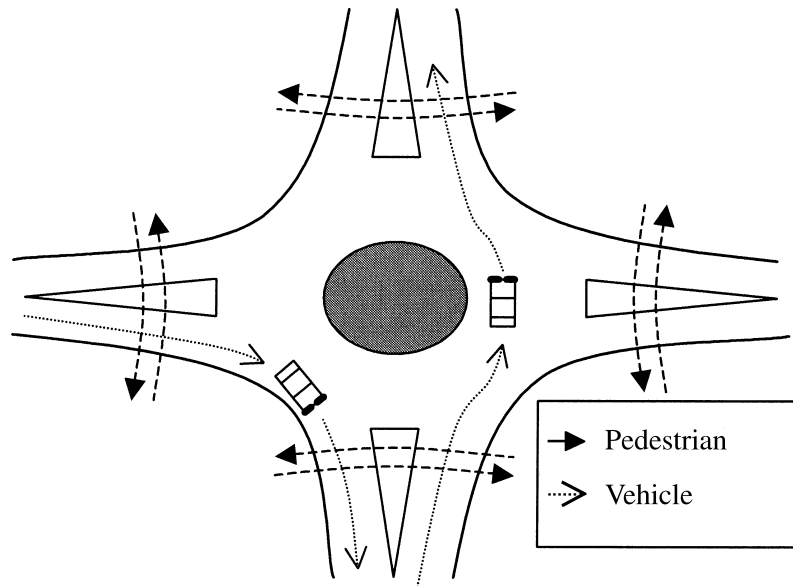


FIGURE 1 Schematic of a roundabout.

3. MAXIMUM PEDESTRIAN CROSSING RATE MODEL

3.1 Introduction

The maximum pedestrian crossing rate (MPCR) is defined as the maximum rate at which pedestrians can cross at a crosswalk under given traffic and geometric conditions. MPCR plays the role of the service rate in queuing models and represents pedestrian crossing capacity on the crosswalk width of 1 m.

Hunt and Williams (1982) suggested four pedestrian alternatives to cross a road that carries two-way vehicle flows such as:

- the pedestrian may wait at the curbside for a suitable gap in combined vehicle flow, then cross directly to the other side;
- the pedestrian may wait at the curbside for a suitable gap in near side flow, cross to the center of the road and wait for a suitable gap in the far side flow before completing his/her crossing;
- the pedestrian may cross between stationary vehicles as, for example, on approaches to traffic signals or pedestrian crossings; and
- the pedestrian may walk along the pavement, while scanning vehicle flow, and cross directly as a suitable gap appears. In this case the pedestrian may cross in two stages, continuing to walk along the center of the road while waiting for a suitable gap in vehicle flow to enable him to finish crossing.

The second alternative has been assumed in the study of roundabouts below, while the third represents the case of the signalized intersection.

3.2 Methodology

The proposed MPCR model for roundabouts relies on the probabilistic gap acceptance process, while the MPCR model for signalized intersections employs Virkler and Guell's formula (1984).

Proposed delay models follow the principals of queuing theory. The *Highway Capacity Manual* (National Research Council 1997) assumed that the characteristics of pedestrian flow are similar to those for vehicle flow. In other words, the fundamental relationships between speed, density, and volume for pedestrian flow is analogous to vehicle flow. The assumption makes it possible for pedestrian delay models to follow the queuing theory model. A queuing theory model is characterized by the maximum permissible number of customers, the number of customers requesting service, and the distribution of inter-arrival time.

Assuming random arrivals (M), random departures (M), one server, and service on vehicles in the order of arrival (FIFO), typical functions for the M/M/1 (∞ , FIFO) queuing theory model can be introduced to pedestrian crossings as:

$$\rho = v/\mu \quad (1)$$

$$L_q = P_0 (v/\mu)^2 / (1 - v/\mu) \quad (2)$$

$$W_q = L_q / v \quad (3)$$

where

ρ = pedestrian traffic intensity;

v = pedestrian arrival rate (ped/h/m), i.e., the number of customers requesting service per unit time;

μ = MPCR (ped/h/m), i.e., the permissible number of customers to be served;

L_q = expected queue length (ped);

P_0 = proportion of time that system is empty, i.e., in the 0 state; and

W_q = waiting time in queue (sec).

3.3 Study Assumption

Basic experimental assumptions are made for simplification and in order to represent the prevailing conditions. They are as follows:

- The intersection is 4-legged and all approaching and exiting volumes are identical;
- The cycle length of signalized intersections ranges from 60 to 120 sec;
- All vehicles have the length of 6.1 m and their acceleration rates are 3.0 m/sec^2 with the approaching speed of 64 km/h (40 mph). Lower speeds are frequently observed in roundabouts. However, the selection of the higher speed intends to provide a conservative result because lower speed at roundabouts is expected to result in higher MPCR and less delay;
- Vehicle perception-reaction is 1.5 sec;

- The lane width of roundabouts is 4.0 m and at signalized intersection 3.7 m;
- Pedestrian walk speed is 1.2 m/sec, with a headway of 2.0 sec and pedestrian perception-reaction time of 1 sec; and
- The width of crosswalk is 1.0 m, for compatibility with the definition of MPCR which represents pedestrian crossing capacity on a crosswalk width of 1 m.

3.4 MPCRs at Roundabouts

For the derivation of a formula to obtain MPCR for this pedestrian crossing under the roundabout design, some additional assumptions are required. These include the following:

- A pedestrian waits for at least the minimum gap before crossing an one-way flow;
- Pedestrians are enough to ensure continuous flow; and
- Vehicle arrival intervals follow the exponential distribution without bunched flow.

The probability density function is expressed as:

$$f(T) = \lambda \cdot e^{-\lambda T} \quad (4)$$

where

$f(T)$ = probability of a gap equal to a time interval T ,
 T = variable of interval between vehicle arrivals, and
 λ = vehicle arrival rate (veh/sec).

The probability of an arrival interval that allows k pedestrians cross the street is

$$p(k) = \int_{t+(k-1)t'}^{t+kt'} f(T) dt - [f(T)]_{+kt'} \quad (5)$$

where

t = time needed by a pedestrian to cross a roadway (sec),
 t' = headway between pedestrians (sec),
 $t+(k-1)t'$ = acceptable gap for k pedestrians (sec), and
 $t+kt'$ = acceptable gap for $(k+1)$ pedestrians (sec).

This function can be rewritten as:

$$p(k) = -e^{-\lambda t + k\lambda t'} (1 - e^{\lambda t'}) - \lambda e^{-\lambda t - k\lambda t'} \quad (6)$$

Thus, the number of average pedestrian crossings per interval (or per gap) per second (ped/gap/sec) is,

$$\alpha = \sum_{k=0}^{\infty} kp(k) \quad (7)$$

That is,

$$\alpha = -e^{-\lambda t} (1 - e^{\lambda t'}) \sum_{k=0}^{\infty} k e^{-k \lambda t'} - \lambda e^{-\lambda t} \sum_{k=0}^{\infty} \lambda e^{-k t'} \quad (8)$$

and

$$\mu_r = 3600 \cdot \lambda \cdot \alpha \quad (9)$$

where

μ_r = MPCR at roundabouts (ped/h/m), and
(3600* λ) = average veh/h or average number of gap/h.

The above function could be rewritten as:

$$\mu_r = 3600 \cdot \lambda \left[-e^{-\lambda t} (1 - e^{\lambda t'}) \frac{e^{-\lambda t'}}{(1 - e^{-\lambda t'})^2} + \lambda e^{-\lambda t} \frac{e^{-t'}}{(1 - e^{-t'})} \right] \quad (10)$$

Figure 2 shows the relationship between MPCR and traffic volume at roundabouts based on Equation (10) for 2-lane and 4-lane 2-way roadways. It is assumed that a dividing island is present. Dividing island gives pedestrians more chance to cross the roadway because it allows for selection of smaller gaps between approaching vehicle traffic.

In the case of 2-lane, 2-way roadway, assuming the ideal saturation flow of 1900 passenger cars per hour per lane (pcphpl), it is shown that there is still room for pedestrian crossing on the oversaturation state. Based on Figure 2, MPCR is 360 ped/h/m (6 ped/min/m) at the threshold of the oversaturation state for the 2-lane, 2-way roadway.

3.5 MPCRs at Signalized Intersections

Pedestrian phases at the signalized intersection consist of red, FDW (Flashing Don't Walk), and pedestrian green (Walk) indications. It is assumed that a pedestrian starts crossing only during the pedestrian green indication. The FDW phase is considered as "clearance time" and depends on the crosswalk length and the pedestrian walking speed.

Virkler and Guell (1984) recommended Equation (11) for calculation of the total green time. They used the term "crossing time" as the lower limit for green plus amber time.

$$T_c = S + (L_c/V) + H(N/W_d) \quad (11)$$

where

T_c = crossing time (sec),
 S = pedestrian starting time (sec),
 L_c = length of crosswalk (m),
 V = walking speed (m/sec),
 H = headway between persons (sec/ped·m),
 N = number of pedestrians, and
 W_d = crosswalk width (m).

If the number of pedestrians, N , is obtained from Equation (11) it could be easily transformed to MPCR considering the portion of the crossing time, T_c , over the given cycle length. Therefore,

$$\mu_{sg} = 3600 (T_{cl} - S - (L_c / V)) W_d / (H \cdot C) \quad (12)$$

where

μ_{sg} = MPCR at signalized intersections (ped/h/m),
 T_{cl} = crossing time per cycle (sec), and
 C = cycle length (sec).

Figure 3 shows the resulting MPCRs, which are calculated in terms of crosswalk length and cycle length. As expected, MPCRs increase when cycle lengths are longer or when crosswalk lengths are shorter.

4. PEDESTRIAN DELAY AT ROUNDABOUTS

The pedestrian delay at roundabouts can be estimated using MPCR (as the capacity of the crosswalk) and queuing theory concepts. The total pedestrian waiting time is defined as the summation of incurred waiting times at the curbside and the dividing island, which is expressed as

$$W_t = \rho_k^2 / (v_k (1 - \rho_k)) + \rho_s^2 / (v_s (1 - \rho_s)) \quad (13)$$

where

W_t = total waiting time (sec),
 ρ_k = pedestrian arrival rate at the curb / μ_k ,
 ρ_s = pedestrian arrival rate at the dividing island / μ_s ,
 v_k = pedestrian arrival rate at the curb (ped/h/m),
 v_s = pedestrian arrival rate at the dividing island (ped/h/m),
 μ_k = MPCR during a given green time at the curb (ped/h/m), and
 μ_s = MPCR during a given green time at the dividing island (ped/h/m).

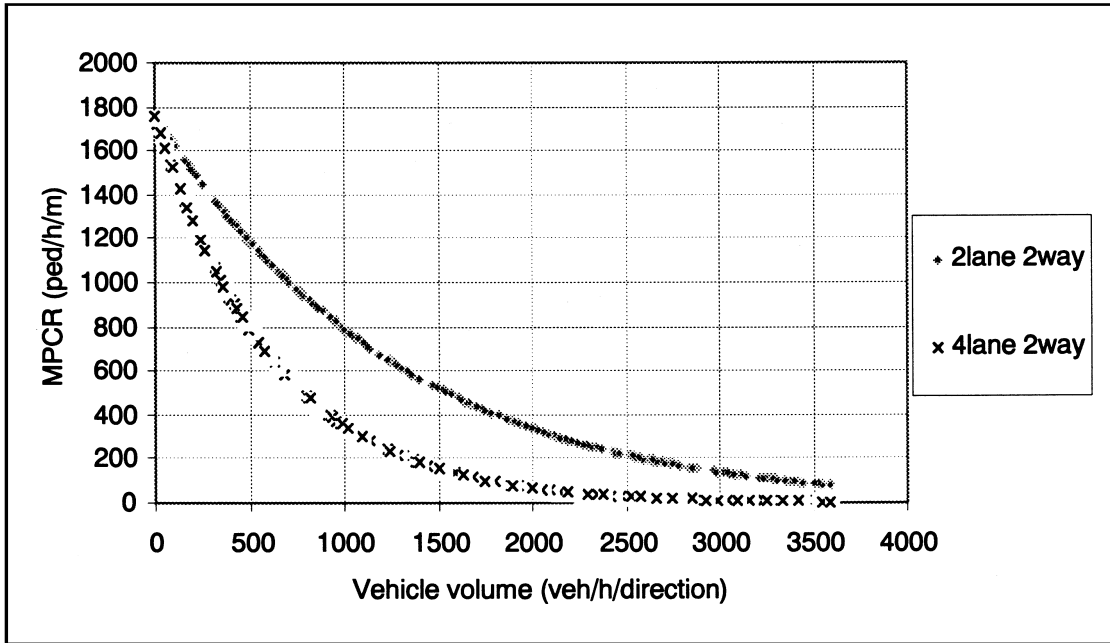


FIGURE 2 MPCR at roundabouts.

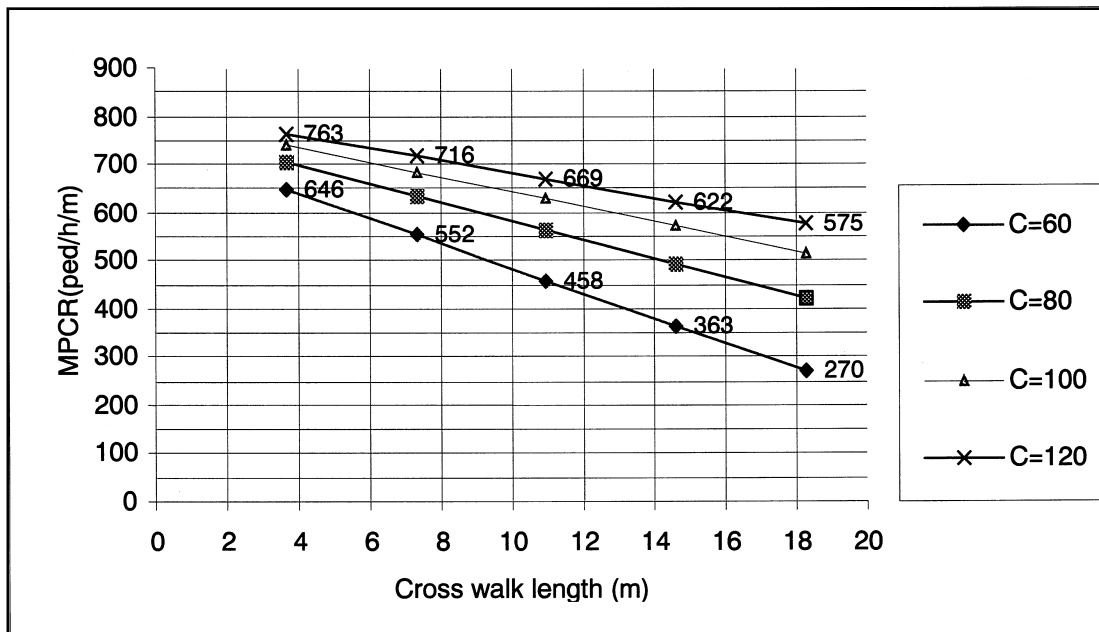


FIGURE 3 MPCR at signalized intersections.

5. PEDESTRIAN DELAY AT SIGNALIZED INTERSECTIONS

Hunt and Williams (1982) suggested that pedestrian delay at pelican crossings is the function of the vehicle flow rate and cycle length. Noland (1996) expressed the average delay of pedestrians as a function of the cycle length and the pedestrian interarrival time in the signalized intersection.

In this study, queuing theory is introduced to pedestrian delay estimation at signalized intersections. The proposed model estimates delay as a function of cycle length and pedestrian arrival rate. The average delay follows the queuing model during the pedestrian walk phase and can be expressed as:

$$W_q = 3600 (v/\mu)^2 / (v(1 - v/\mu)) \quad (14)$$

where

W_q = average waiting time due to queue (sec/ped),
 v = pedestrian arrival rate (ped/h/m), and
 μ = MPCR during a pedestrian walk phase (ped/h/m).

During the waiting phase, the average delay can be simplified into:

$$W_D = \frac{1}{2} (C - G) \quad (15)$$

where

W_s = average waiting time due to signal (sec/ped),
 C = cycle length (sec), and
 G = time for pedestrian green phase (sec).

Considering each portion of pedestrian arrivals during each time allocation, the average total delay for a pedestrian (W_t , sec/ped) in a signalized pedestrian crossing can be expressed as:

$$W_t = 0.5(C - G)^2/C + G/C \times \rho^2 / (v(1 - \rho)) \quad (16)$$

6. DISCUSSION

Table 1 compares MPCRs of both intersection alternatives, namely roundabouts and signalized intersections. Roundabouts provide more pedestrian capacities under the vehicular volume up to 1100 veh/h/direction at 2-lane, 2-way intersections. Compared to a signalized intersection with cycle length of 60 second, a roundabout outperforms the signalized alternative for vehicular volumes up to 1400 veh/h/direction.

TABLE 1 Pedestrian Capacity and Vehicle Volume Comparison

Vehicle Volume (veh/h/ direction)	MPCR (ped/h/m)					
	2-Lane 2-Way			4-Lane 2-Way		
	Roundabout	Signalized Intersection		Roundabout	Signalized Intersection	
		C=60sec	C=120sec		C=60sec	C=120sec
500–600	1094	552	716	671	363	622
601–700	1009	552	716	570	363	622
701–800	931	552	716	485	363	622
801–900	858	552	716	412	363	622
901–1000	790	552	716	349	363	622
1001–1100	727	552	716	296	363	622
1101–1200	669	552	716	251	363	622
1201–1300	615	552	716	213	363	622
1301–1400	566	552	716	180	363	622
1401–1500	520	552	716	153	363	622

At 4-lane, 2-way facilities, roundabouts are superior to signalized intersections in terms of pedestrian capacity for the light vehicular volumes only up to 600 veh/h/direction compared to an intersection with a cycle length of 60 sec.

Figures 4 and 5 compare the expected delay at roundabouts and signalized intersections for various pedestrian flow rates, assuming that the MPCR at roundabouts and signalized intersections are identical. Figure 4 shows that 2-lane, 2-way roundabouts with approaching volume less than 1000–1200 veh/h/direction provide delays lower than signalized intersections regardless of pedestrian flow rate. Figure 5 shows that roundabouts outperform signalized intersections only when either the pedestrian or the approaching traffic flow rates are not considerable for 4-lane, 2-way crosswalks. The underlying reason is that pedestrian delay at roundabouts is very sensitive to both types of volume rates.

7. SUMMARY AND CONCLUSIONS

A formula for maximum pedestrian crossing rate (MPCR) calculation at roundabouts was introduced. This formula can be used for calculation of pedestrian capacity in the case of a new design or an operational evaluation of roundabouts.

For signalized intersections, an existing formula was employed for calculation of MPCR. It was based on the cycle and crosswalk length. Longer cycle lengths were associated with higher pedestrian capacities, while longer crosswalk length resulted in lower capacity values.

Two delay models were also proposed in order to calculate and compare delays at the two study intersection alternatives, namely roundabouts and signalized intersections. The underlying theory in delay model development is queuing theory.

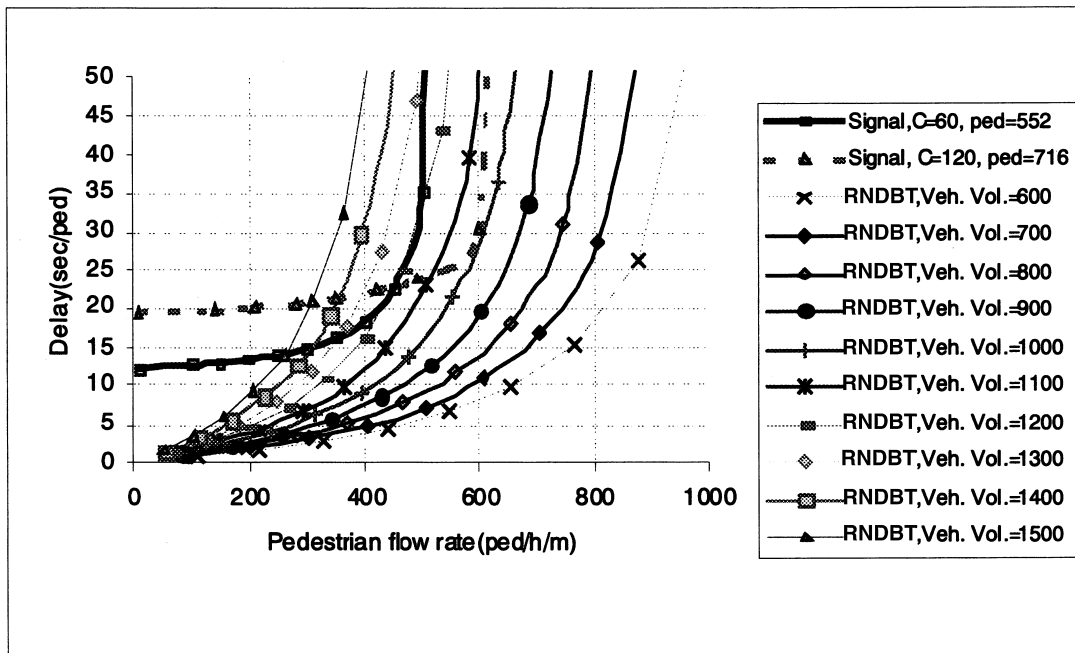


FIGURE 4 Averaged pedestrian delay comparison at 2-lane, 2-way roadways.

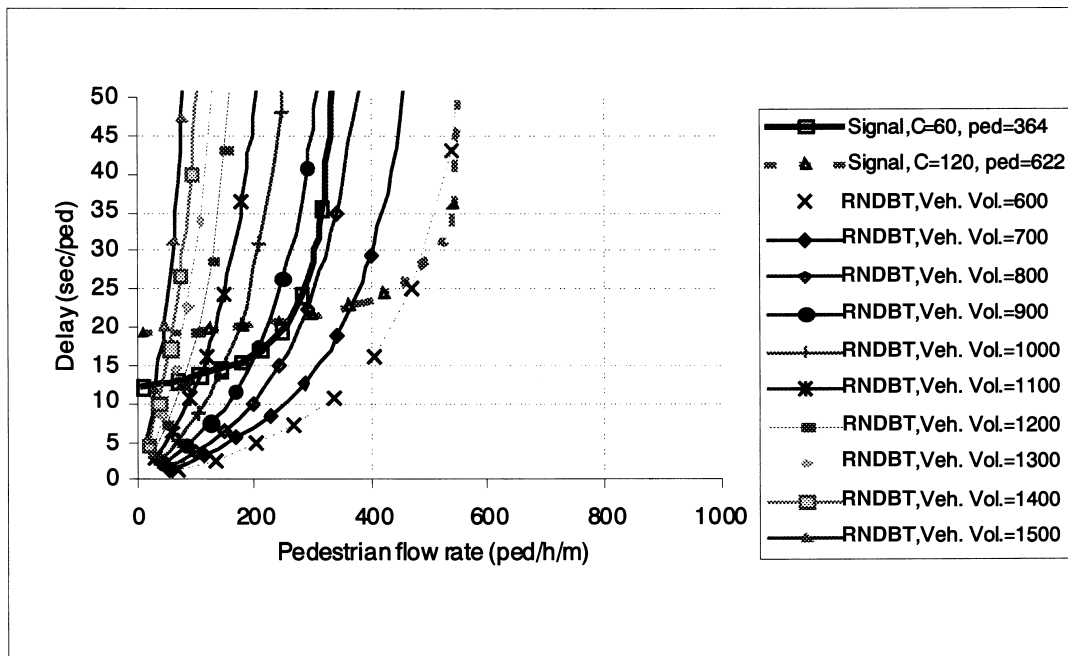


FIGURE 5 Averaged pedestrian delay comparison at 4-lane, 2-way roadways.

The delays at roundabouts and signalized intersections are controlled by pedestrian intensity (pedestrian arrival rate over MPCR) resulting in delay curves that are polynomially shaped according to pedestrian arrival rate. At roundabouts, the existence of the dividing island contributes to lower total delay as pedestrians experience a two-staged delay. At signalized intersections, the delay model employed static delay due to signal as well as queuing theory concept.

From the comparison of pedestrian delay values under the study assumptions, the hypothesis that roundabouts result in lower pedestrian delay under light vehicle traffic and light pedestrian demand was accepted. Especially for 2-lane, 2-way crosswalks with approaching volume less than 1000 to 1200 veh/h/direction, roundabouts provided less pedestrian delay, regardless of pedestrian flow rate when compared to signalized intersections with cycle length of 60 to 120 sec.

All results presented above were based on theoretical analysis and intended to provide basic insight into the pedestrian capacity comparison between two competing intersection alternatives. As the model is based on gap acceptance theory, potential queue backups could not be analyzed with this model. Study of queue back ups as well as model calibration and validation using field data are recommended for future study.

ACKNOWLEDGMENT

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